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On the structural behaviour of variable-geometry oval-trajectory Darrieus wind turbines

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A B S T R A C T

We developed a computational model based on a finite-element mixed formulation with quadratic isoparametric beam elements. We applied this model to the analysis of a blade-wagon: a novel structure characteristic of an innovative concept in wind-power called VGOT Darrieus turbine. We studied the structural behaviour of its main components: chassis, suspension and blade, using combinations of beam/bar elements in an appropriate assembling. We defined a set of parameters to characterize the structural behaviour which help to understand the contribution of the different components and assist the process of redesign.

1. Introduction

It is a fact that due to economics-of-scale reasons cost effectiveness of wind turbines increases with size. During the last 25 years the size of the state-of-the-art wind machine has been increasing systematically but the actual technology of horizontal-axis wind turbines would ultimately reach its limits. Very large sizes would create a number of gigantism problems in rotor design and low rotational speed associated with large radii would complicate the coupling with the electrical generator. Besides, there are geographical regions (like Patagonia in Argentina) characterized by a vast wind resource. Mean speeds in some areas double those recorded at European locations for which commercially available high-power wind turbines were designed. Regarding that the energy carried by a wind stream depends on the cube of its speed, those regions offer an enormous potential in terms of energy resources. Hence, it is worthwhile to explore innovative concepts in extra-large wind-power plants to overcome the size limits of the actual wind-power technology and being able to exploit the renewable energetic potential that high-wind-speed regions offer. To this end, an innovative concept of wind turbine based on the Darrieus-type rotor had been introduced [1].

In a traditional Darrieus turbine, the blades rotate around a central vertical axis. In the VGOT (variable-geometry oval-trajectory) concept proposed in Ref. [1], each blade instead of rotating around a central vertical axis slides over rails mounted on a wagon formed by a reticulated structure supported by standard train bogies (see Figs. 1 and 2). Each wagon contains its own electrical generation system coupled to the power-wheels and the electricity is collected by a classical third rail system [2,3]. With the VGOT design, if we kept constant the velocity of the wagons (i.e. the tangential speed of the blades), we can increase the area swept by the blades (and hence the rated power of the plant) without the low-rotational-speed problems associated to a classical Darrieus rotor of large diameter. The blade-wagon elements of a VGOT Darrieus, not being solidly affixed to a central axis, could move following a non-circular trajectory (see Fig. 3). For certain locations where the compass rose shows a preferential direction it is possible to optimize the energy-conversion efficiency of the entire plant by increasing the portion of transit perpendicular to the direction of the incoming wind. Along the perpendicular tracks, the blade generates the higher output-power, while along the portions where the trajectory is in-line with the incoming wind the blade-wagon not only does not produce energy but also even consumes it taking power from the rest of the plant to keep on moving. Thus, extending those portions of the path perpendicular to the wind by the addition of straight tracks the overall energy-conversion efficiency of the plant increases. The idea of mounting a blade on a wagon with the aim of generating electricity has been proposed

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Fig. 1. Perspective view of a blade-wagon.

before (see for example Fig. 1.6, Section 1.1.3 in Ref. [4], among others), but with the VGOT concept we intend to carry on a systematic study of the real feasibility of such a design, being the analysis of the structural behaviour a fundamental step.

When undertaking the study of the structural behaviour of the blade-wagons of a VGOT Darrieus several particularities arise that make it different from other studies in beam-reticulated structures. The analysis of the blade offers some particular features too. It has a variable section of complex shape and the aerodynamic loads depend on both, the position of the blade-wagon along the path and the height from the ground. In that sense, computation of the aerodynamic loads is not trivial since, due to the interaction of the adjacent blades, the plant works as a whole and it is not possible to analyze the aerodynamic behaviour of each blade-wagon separately. A special code was created to model this complex aerodynamic behaviour [5–9] and its results were used as input loads for the present study. When studying the three-dimensional reticulated structure of the wagon chassis, the effects of its coupling with the blade and the suspension system should be considered, together with the effects of the added mass of the components and the ballast placed to improve the stability of the wagon. The suspension system should absorb the fluctuating aerodynamic loads and eventual imperfections in the layout of the rails, for if they were transmitted directly to the bogies and the rails, they would compromise the operational life of the plant. In the following sections we shall describe the development of the computational model that we used to simulate the behaviour of this unique structure.

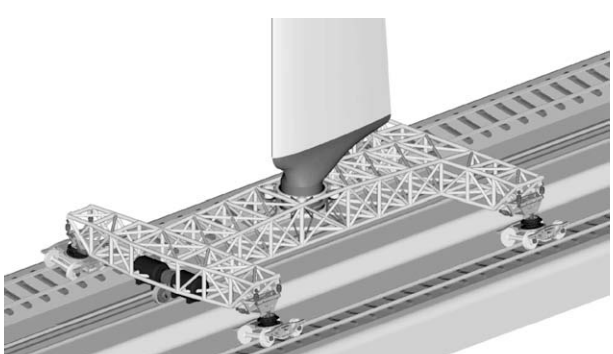

Fig. 2. Structural configuration of a blade-wagon showing the bogies, the suspension system and the electrical generators coupled to their driving wheels.

2. The structural problem

For the first stage of our study of the VGOT turbine, we used a linear analysis approach (i.e. small displacements, small deformations and linear elastic homogeneous material were assumed). This analysis will be very precise in normal operational conditions at rated power where real work conditions fulfil the proposed hypothesis. This linear analysis provides an essential tool for project purposes and serves as first step for a future study on the non-linear behaviours that are likely to appear when the plant is working at extreme operational conditions.

In this stage of our work, we used beams and bars to represent the reticulated structure of the wagon, the blade and the suspension. The blade was modelled by 50 variable-section beam elements; the blade-section chord length varies from 8 m at the bottom to 4 m at the tip. Each tubular beam of the three-dimensional reticulated structure of the wagon was modelled by one beam element of constant section. Depending on which portion of the structure the beam belonged to, the exterior and interior diameters differ according to design. The details of the suspension system mechanism are still at project stage, but its behaviour can be satisfactorily modelled by an assembling of four two-node bar elements located at each one of the four ends of the wagon in place of the actual suspension mechanism. This helps us to determine the overall stiffness required from the suspension system in order to keep the stability of the wagon and the aerodynamic configuration. Another mechanism that should be modelled to study the whole structural group of the generating wagon is the blade attachment. This device should link the blade bottom with the reticulated structure and also includes the positioning mechanism. It was modelled by beam elements of extremely high stiffness which is quite realistic considering that stiffness is a characteristic inherent to the functionality of this device.

The structure of the VGOT Darrieus is mainly subject to loads of aerodynamic origin. As it was mentioned above, aerodynamic loads were calculated by means of a double-multiple streamtube model that was the result of previous work [5–9] and were applied to the blade as a distributed load per unit length. These loads varied in function of both the wagon position along the path and the height from the ground, Fig. 4a and b shows the aerodynamic load per unit length in the chord-wise and chord-normal directions (f_{chws}, f_{chnor}) for different heights along the blade in function of the parametric position along the path s (i.e. s goes from 0 to 1 to complete the cycle with its origin located half way on the upwind straight track). The distributed loads acting on the blade are obtained by projecting f_{chws} and f_{chnor} onto a global system of coordinates aligned with the rails. We also considered loads due to the weight of the chassis, the blade and the mechanical devices, and also inertial loads due to the centrifugal acceleration. The geometrical boundary conditions apply onto the suspension support points where displacement is restricted in vertical and transverse directions. Being this a bond of support type, bond reactions act only in one sense (i.e. pressing the wheels against the rails) and it was necessary to verify that contact was always preserved. In those cases where this condition was not fulfilled, the ballast was modified to increase the wagon's stability. To take into account the effects of eventual imperfections and misalignment of the rails due to aging, we introduced randomly simulated displacements of the points of the structure where the